THE 511 keV EMISSION OF THE ELECTRON-POSITRON ANNIHILATION IN THE MILKY WAY

POSITRON HISTORY

1928 (Dirac): Prediction of “anti-electron”

1932 (Anderson): Discovery in cosmic rays

1934 (Klemperer and Chadwick): Annihilation gamma-ray line at 511 keV

1934 (P. Joliot and I. Curie): Production in β^+-decay

1934 (Mohorovicic): Prediction of ***positronium***

1951 (Deutch): Production of positronium

1956 (Ginzburg): p-p collisions in cosmic rays produce e^+

1964 (Shong et al.): Discovery of positrons in cosmic rays

1969 (Stecker): In ISM, most e^+ should form positronium

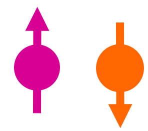
Annihilation of positrons with electrons

Either **directly** (2 γ of E = 511 keV each),
or, after formation of **Positronium (Ps)**, with probability **f**

Probability :1/4

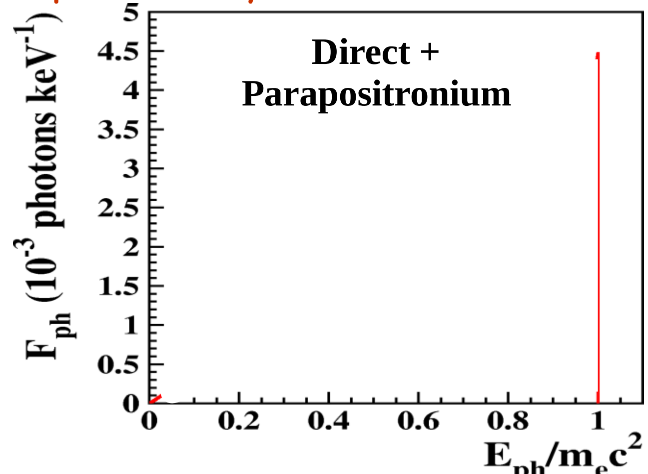
Parapositronium

$^1S_0$



S=0
(singlet)

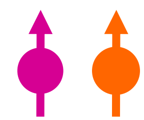
τ = 1.25 10^{-10} s ⇒ 2 γ of E = 511 keV



Probability :3/4

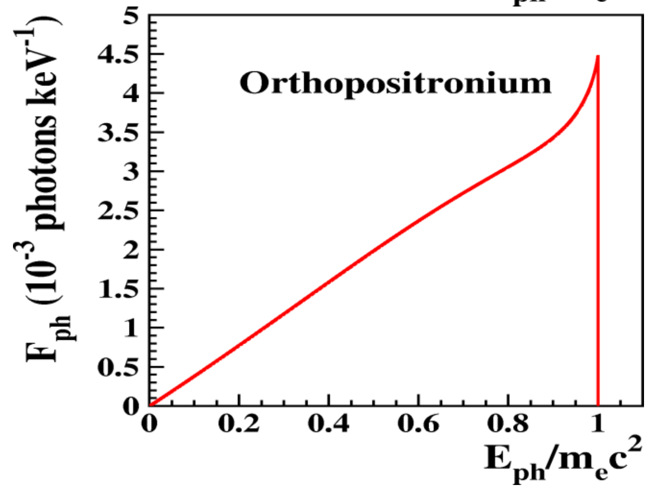
Orthopositronium

$^3S_1$



S=1
(triplet)

τ = 1.4 10^{-7} s ⇒ 3 γ of E ≤ 511 keV



$F_{2\gamma}$ = 2(1-f) (direct) + 1/4 2 f (paraPs)

$F_{3\gamma}$ = $\frac{3}{4}$ 3 f (orthoPs)

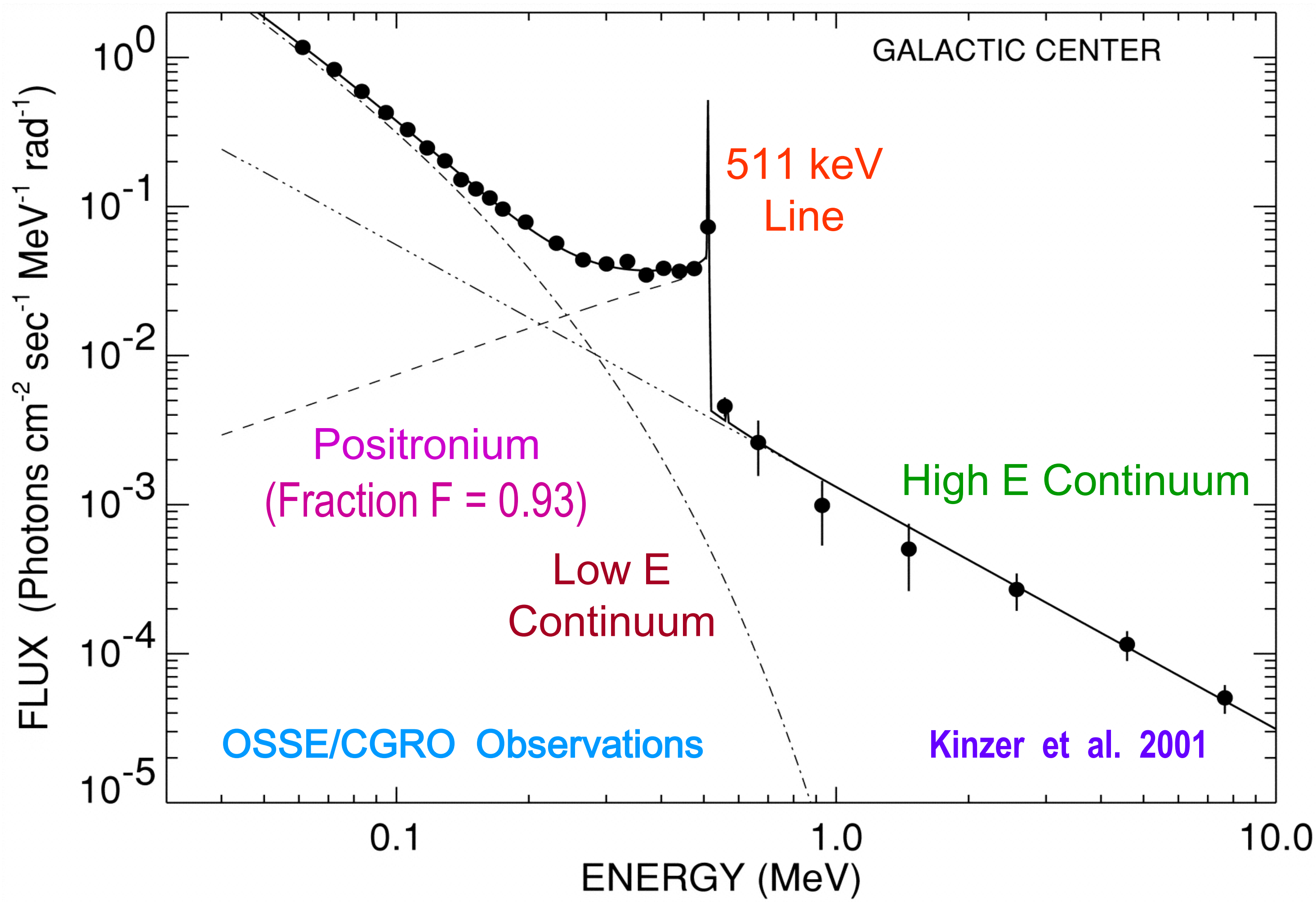
$$f = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})}$$

Positronium fraction

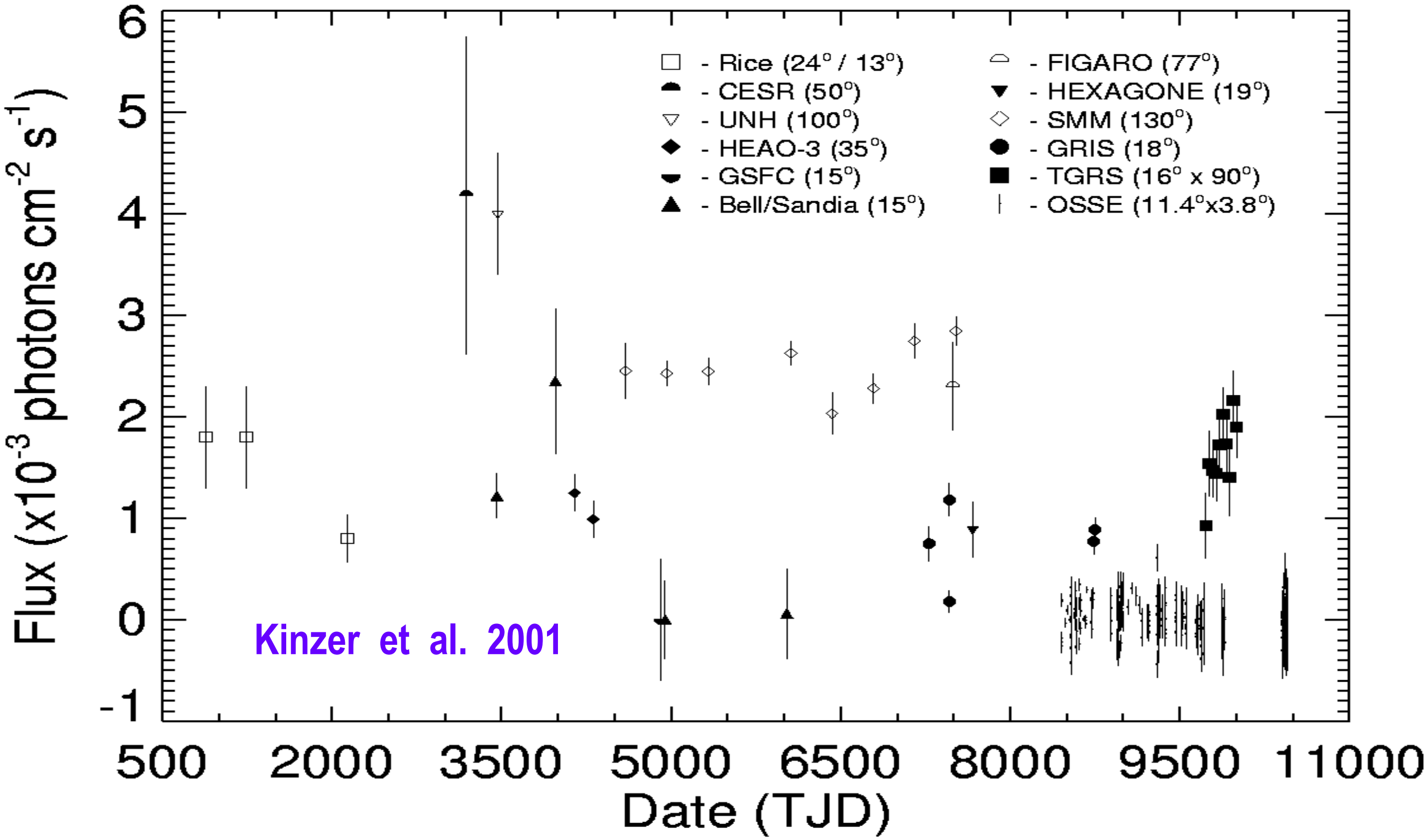
Positron annihilation radiation from the Galactic center region

First (and brightest) γ-ray line detected outside the solar system
(**Johnson et al. 1972**, *Rice U.* Na detector : **Leventhal et al. 1978** *Bell-Sandia* Ge detector)

Flux (~10^{-3} cm^{-2} s^{-1}) + Distance (8 kpc) ⇒ **Luminosity ~10^{37} erg/s (a few 10^3 $L_\odot$)**



511 keV emission measurements in the Galactic Center direction

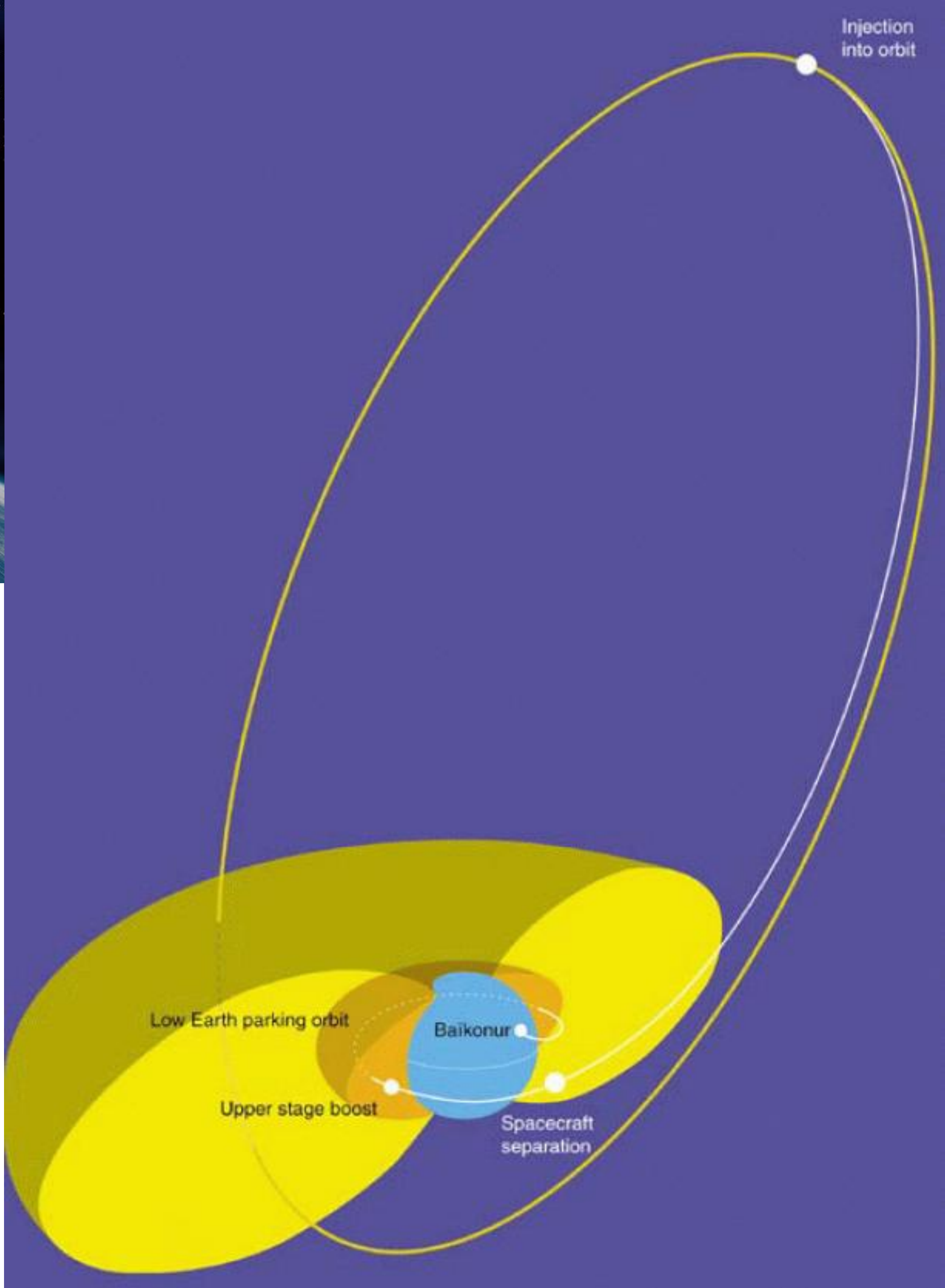


Early reports (80ies) for flux variability not confirmed by OSSE/CGRO

Flux correlated with instrument field of view ⇒diffuse emission

INTEGRAL was launched
on October 22, 2002
by a PROTON rocket
from Baikonur
in Kazakhstan

Largest part of INTEGRAL's orbit is found outside Earth's magnetic (Van Allen) belts, which are full of cosmic ray particles and are sources of background noise for gamma-ray detectors.

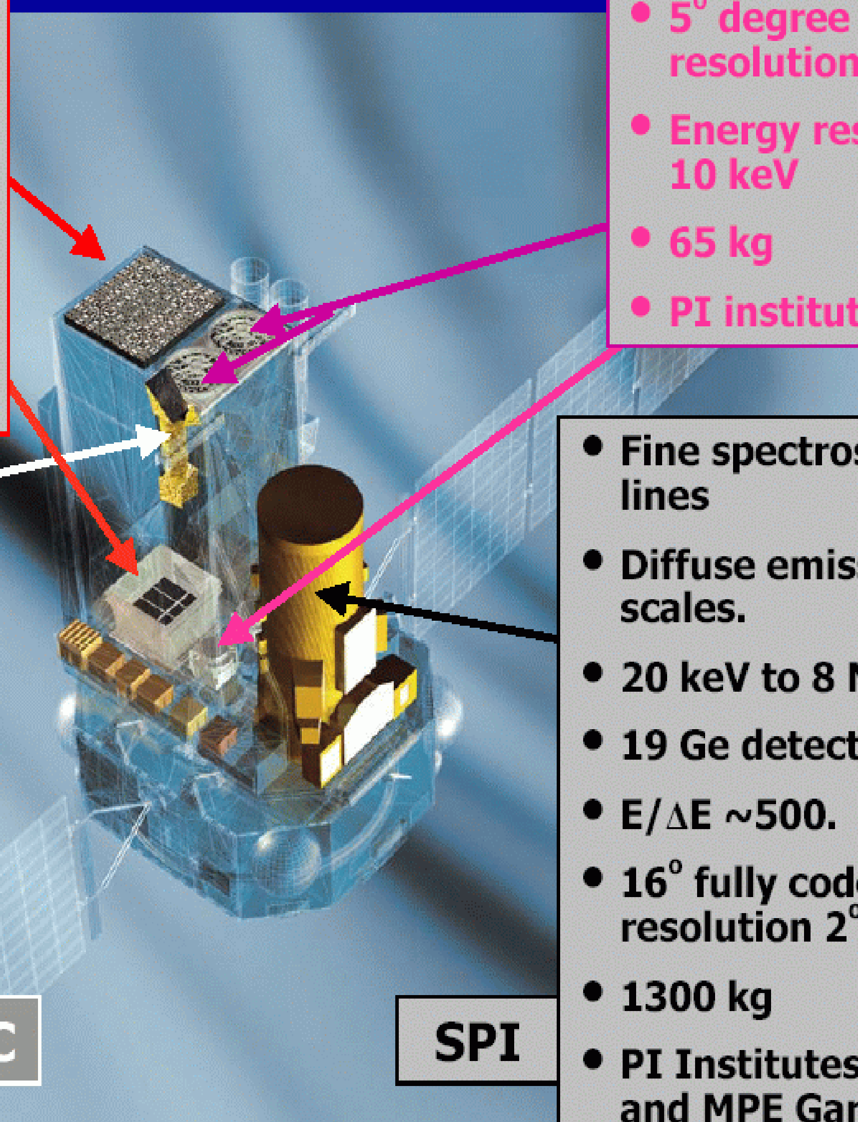


IBIS

- Accurate point source imaging and location.
- Broad lines and continuum.
- 15 keV – 10 MeV
- 16384 CdTe (ISGRI), 4096 CsI (PICsIT) detectors. E/ΔE ~10.
- 9°x 9°degree fully coded FOV. Angular resol 12′ FWHM
- 630 kg
- PI Institutes: IAS Roma (I), CEA-Saclay (F), ITESRE – Bologna (I)

JEM-X

- Source identification and monitoring in X-rays
- 3 –35 keV X-ray monitoring
- Microstrip Xe gas detectors
- 5° degree FOV with 3′ spatial resolution
- Energy resolution of 15% at 10 keV
- 65 kg
- PI institute: DSRI (Dk)



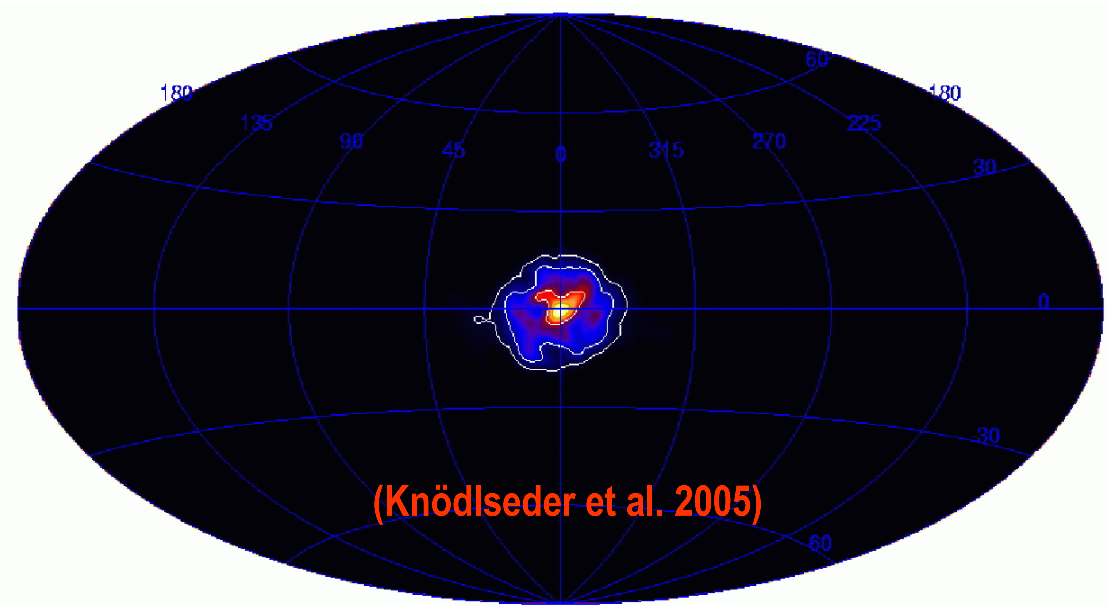
OMC

- Optical monitoring of high-energy sources
- 500 – 600 nm wavelength range
- CCD (2048 x 1024 pixels)
- 5° x 5° FOV, 20″ imaging
- 17 kg
- Sensitivity: 18.2 mag in 1000 s
- PI Institute: INTA/LAEFF (Esp)

SPI

- Fine spectroscopy of narrow lines
- Diffuse emission on > deg scales.
- 20 keV to 8 MeV
- 19 Ge detectors @ 90 K,
- E/ΔE ~500.
- 16° fully coded FOV. Angular resolution 2° FWHM
- 1300 kg
- PI Institutes: CESR Toulouse (F) and MPE Garching (D)

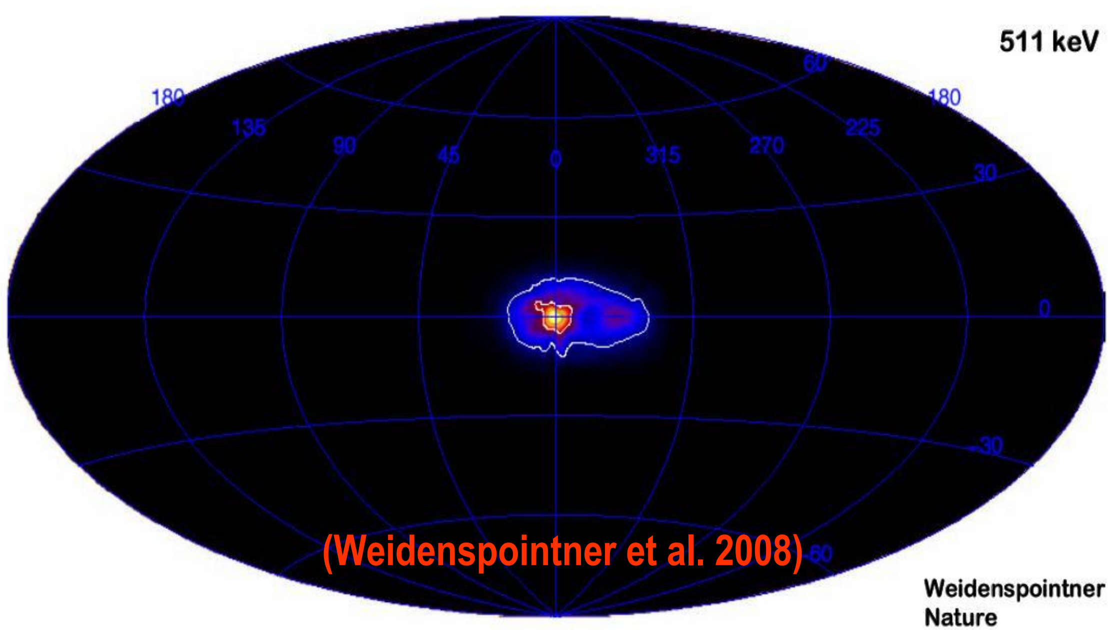
SPI/INTEGRAL all-sky distribution of the 511 keV line of $e^- - e^+$ annihilation



Emission appears strongly peaked towards the **Galactic bulge**

Fitted with a Gaussian of FWHM=8°

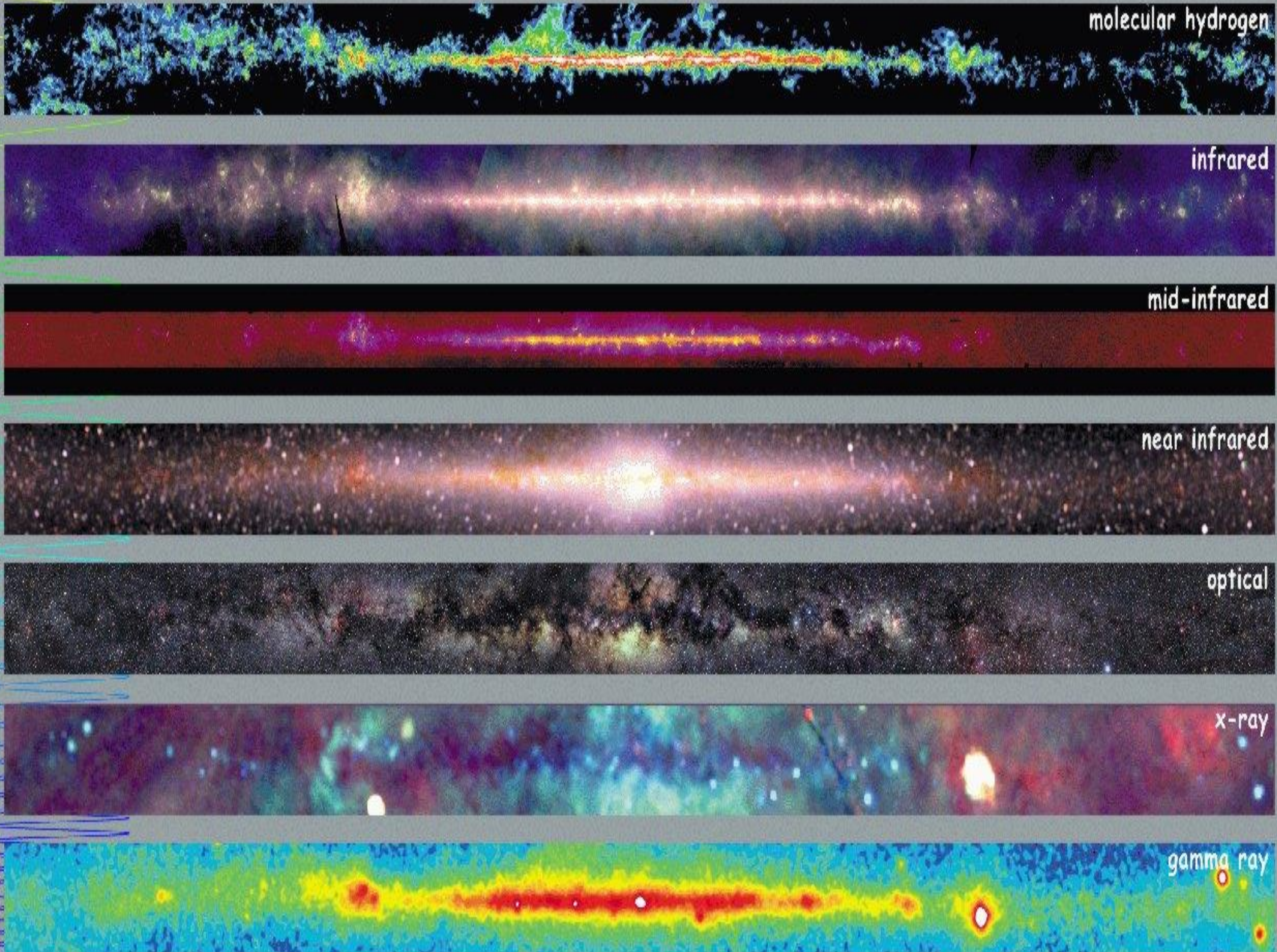
Hints for a **weak disk emission** with Bulge/Disk emissivity ratio B/D > 1



Bulge : $1.2 \pm 0.1\ 10^{43}\ e^+\ s^{-1}$

Disk : $0.8 \pm 0.2\ 10^{43}\ e^+\ s^{-1}$

No equivalent in any other wavelength !


molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray

Requirements from the positron source(s)

1) Total production Rate ***(Steady state)*** **: ~2. 10^{43} e^+ s^{-1}**

~1.2 10^{43} e^+ s^{-1} (Bulge)

~0.8 10^{43} e^+ s^{-1} (Disk)

2) Morphology: Bulge/Disk >1.4

(assuming that positrons annihilate close to their sources)

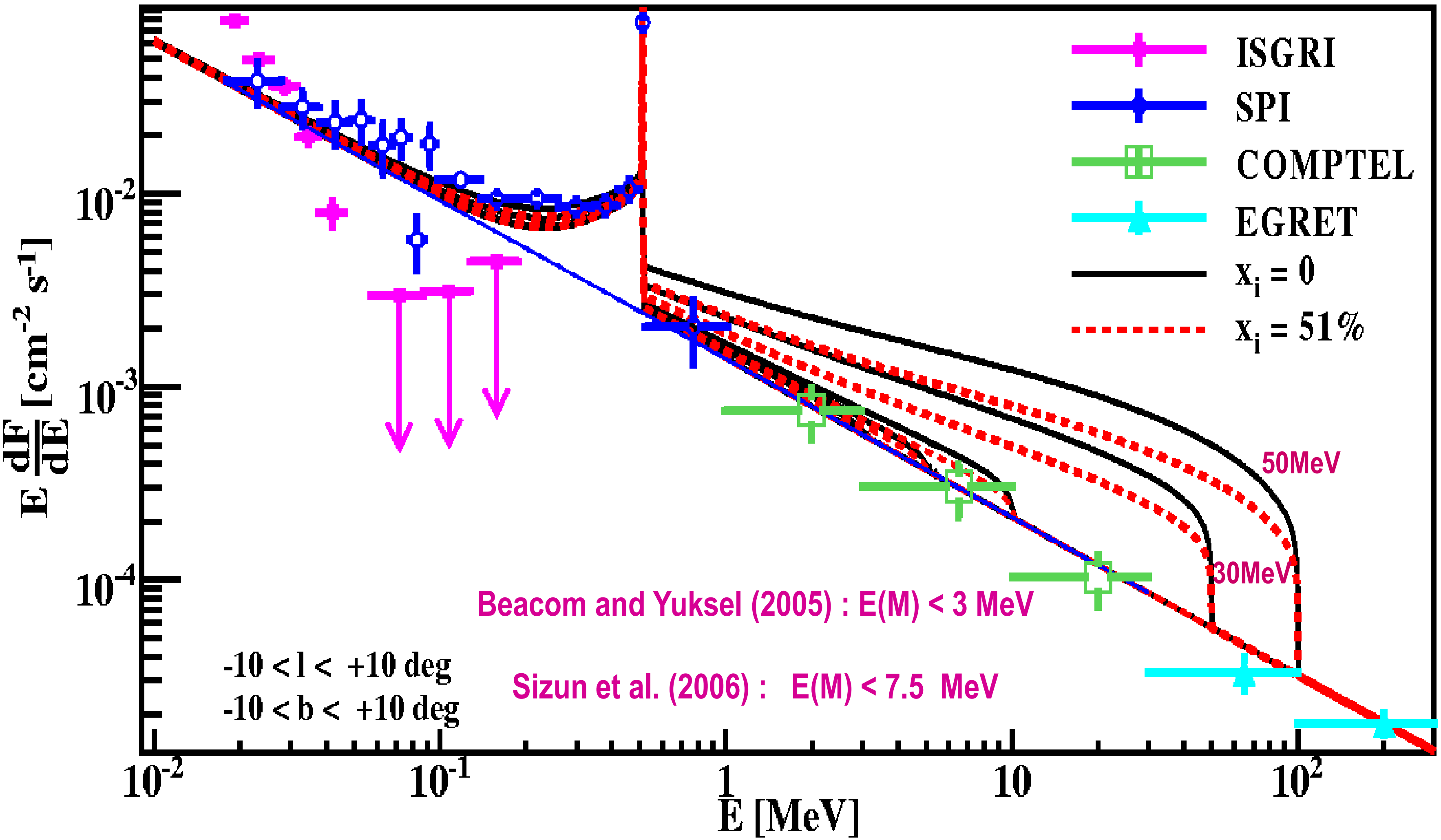
3) Positron injection energy < a few MeV

(constraint from observed GC spectrum in MeV region)

Spectrum in the > MeV region: constrains the energy of *released* e+

(or the mass of their parent dark matter particles)

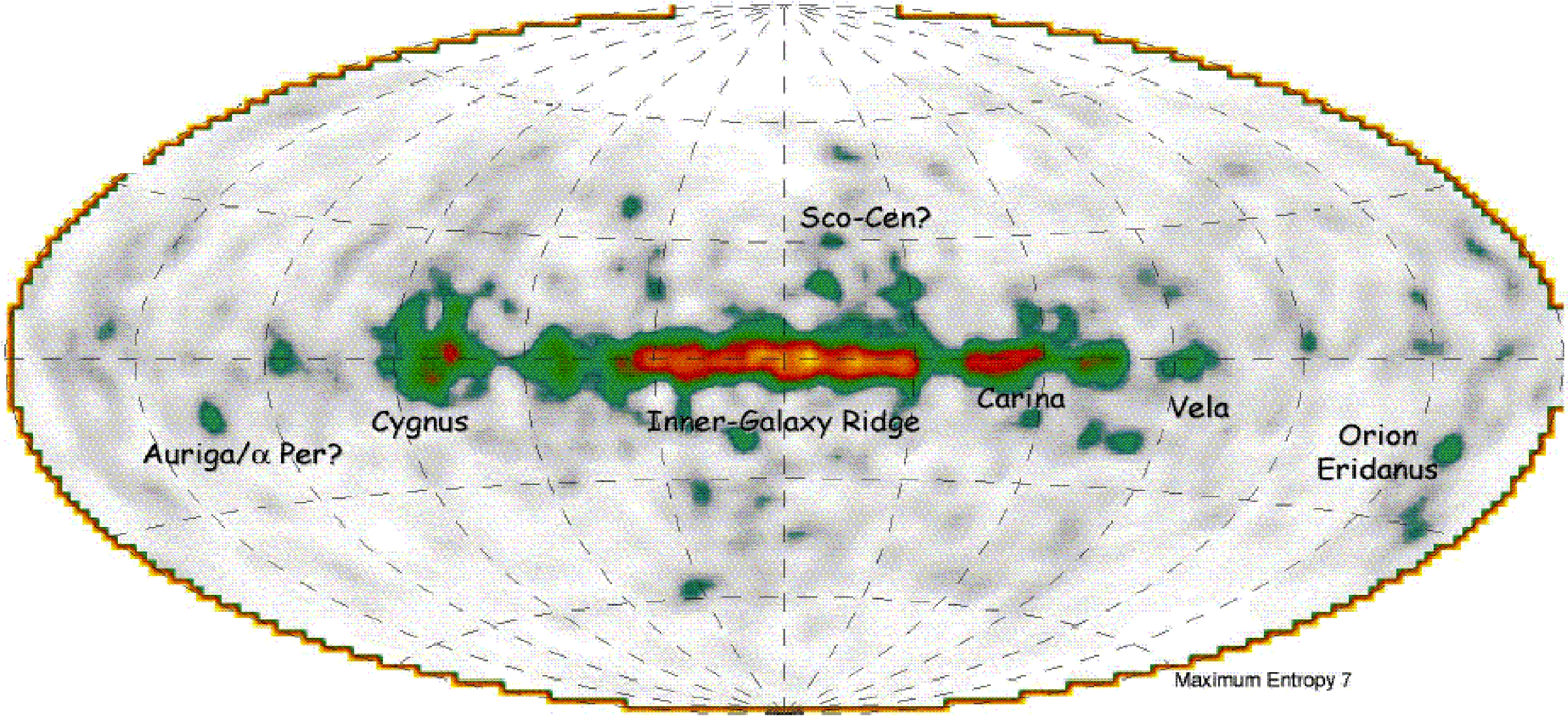
because they may annihilate in-flight



POSITRON SOURCES

I. Stellar Nucleosynthesis of radioactive nuclei

COMPTEL / CGRO legacy: 1.8 MeV map of Galactic ^{26}Al (long lived : $\tau \approx 1$ Myr)



Complete CGRO Mission
(Plüschke et al. 2001)

Total flux: $\approx 4\ 10^{-4}$ cm^{-2} s^{-1} $\Rightarrow$ $\approx$ **2.8 $M_\odot$ of ^{26}Al per Myr**

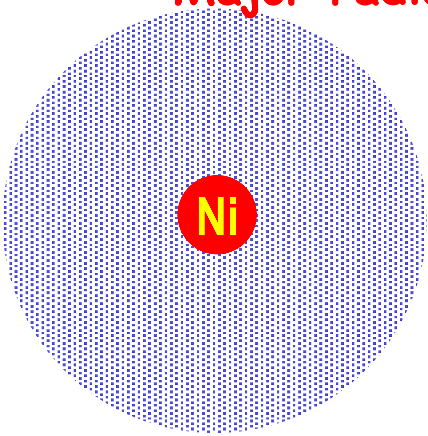
1.8 MeV emission hot-spots in the directions tangent to the **spiral arms** suggest that **massive stars** are at the origin of ^{26}Al

Each ^{26}Al decay releases 0.82 e^+

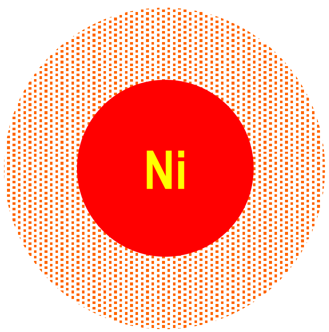
Observed **2.8 $M_\odot$/Myr** correspond to **0.4 10^{43} e^+/s** (= 0.5 SPI disk !)

Positron sources : Medium-lived radioactivity from SN

Major radioactivity in SN : $^{56}Ni \xrightarrow[8.8\ days]{} {}^{56}Co \xrightarrow[113\ days]{0.2\ e^+} {}^{56}Fe$

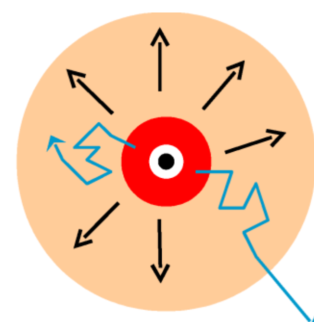


Core collapse SN (Massive stars) $M_{Ni56} \sim 0.07\ M_\odot$ $M_{Envelope} \sim 10\ M_\odot$



Thermonuclear SN (White dwarfs) $M_{Ni56} \sim 0.7\ M_\odot$ $M_{Envelope} \sim 0.7\ M_\odot$

Thermonuclear SN (SNIa): release **more e^+** which **escape easier** (*in principle*) from the expanding envelope than in the case of SNII



Number of positrons produced per SNIa:
$N = 0.19\ M_{Ni56}\ M_\odot\ N_A / 56 \sim 3\ 10^{54}$

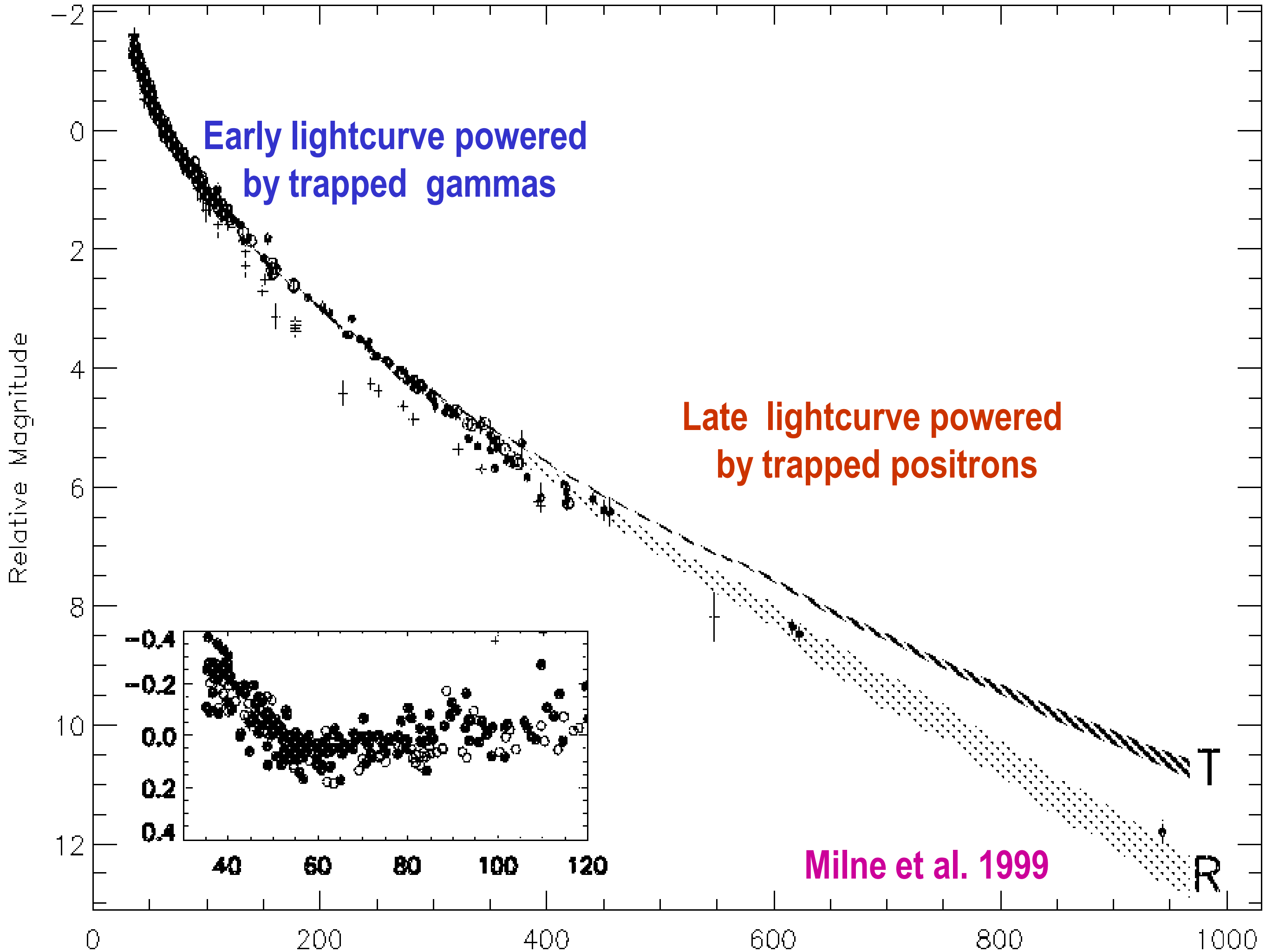
Frequency of SNIa in MW :
$f \sim 0.5 /100\ yr \sim 1.6\ 10^{-10}\ s^{-1}$

Rate of positrons released by MW SNIa:
$R = f\ N \sim 4.5\ 10^{44}\ s^{-1}$

OK if just 3% of them annihilate in the ISM !

What fraction of the e^+ produced by the short-lived Co56 manage to escape the SNIa ejecta?

It depends on unknown intensity and configuration of the supernova magnetic field



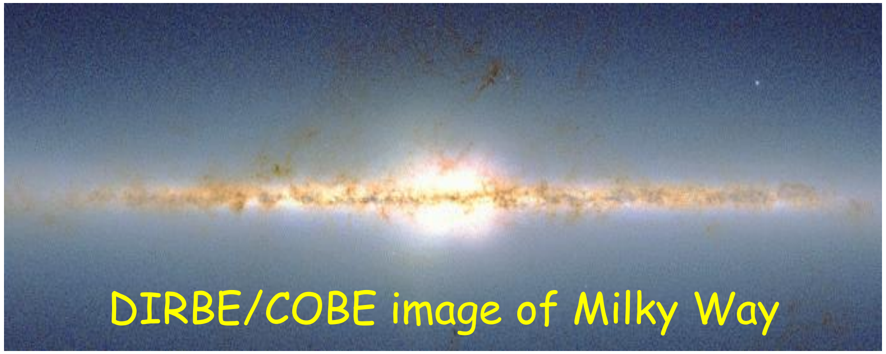
Observations of late lightcurves of SNIa: N ~ 8 10^{52} e^+

(escape fraction f ~ 0.03)

Masses

M_{Bulge} = 1.5 (1-2) 10^{10} $M_\odot$

M_{Disk} = 3. (2.5-3.5) 10^{10} $M_\odot$

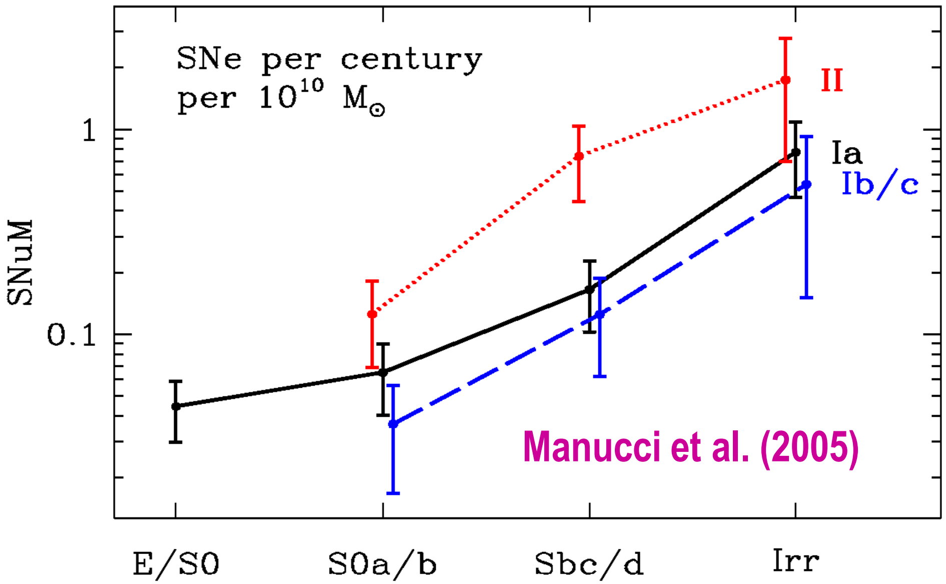


SNIa frequencies

(per 10^{10} $M_\odot$ per 10^2 yr)

F_{Bulge} (E/S0) ~ 0.1

F_{Disk} (Sbc) ~ 0.17



Galactic positron ejection rate from SNIa

L = M x F x N

Assuming N=8 10^{52} e^+ i.e. escape fraction f=0.03

L_{Bulge} ~ 0.4 10^{43} e^+/s

L_{Disk} ~ 1.2 10^{43} e+/s

Total emissivity Ok, BUT… Situation of Bulge/Disk opposite to observations !

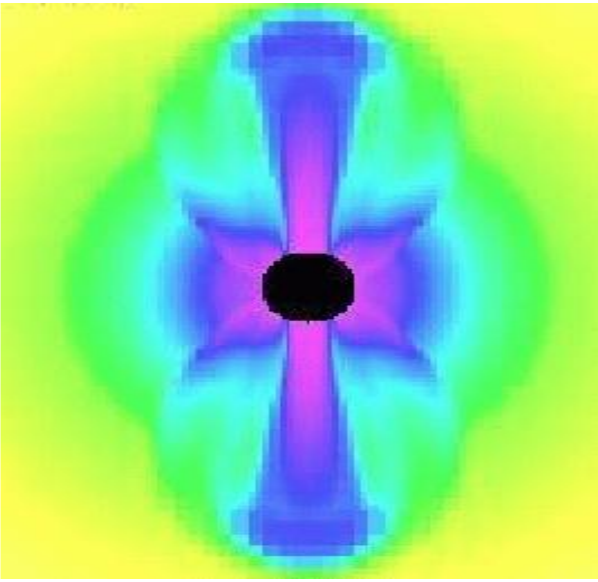
Other sources of positrons from nucleosynthesis?

Decay of Ti44, produced essentially in CC-SN : all positrons escape **(τ ~ 80 yr)**
but: $N_\odot(^{44}Ca) \sim N_\odot(^{56}Fe)/600$ → **e^+ production Rate ~ $3\ 10^{42}\ s^{-1}$**

OK FOR ½ DISK, NOT FOR BULGE

Hypernova(e)/Gamma Ray Burst in Galactic Center ?

(Rudaz and Stecker 1988, Nomoto et al. 2001, Cassé et al. 2003, Parizot et al. 2005)



Hypernova/GRB models suggest/require large amounts of Ni56 (0.5 $M_\odot$) and easier escape of e^+ along the rotation axis *(if one forgets about magnetic fields !)*

But: more massive stars/HN explosions expected in the disk, particularly in the molecular ring…

Also, HN improbable in high metallicity regions, like the GC…
(Stanek et al. 2005, Woosley and Heger 2005)

Novae ?

Nova distribution in M31 extremely peaked in bulge **(Ciardulo et al. 1987)**

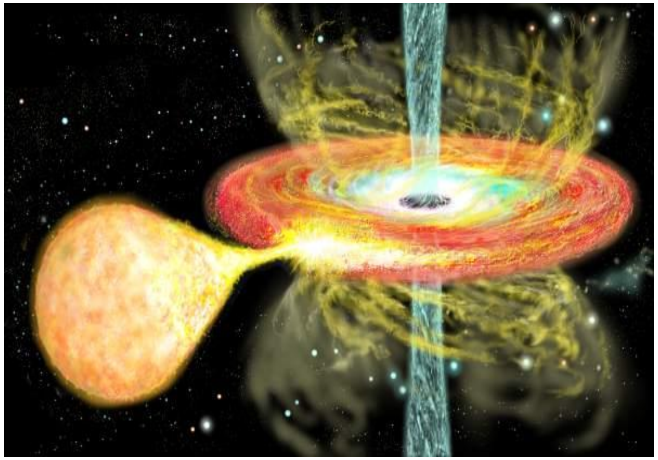
Positron production through ^{13}N(14 min), ^{18}F(2.6 hr), ^{22}Na(3.75 yr)

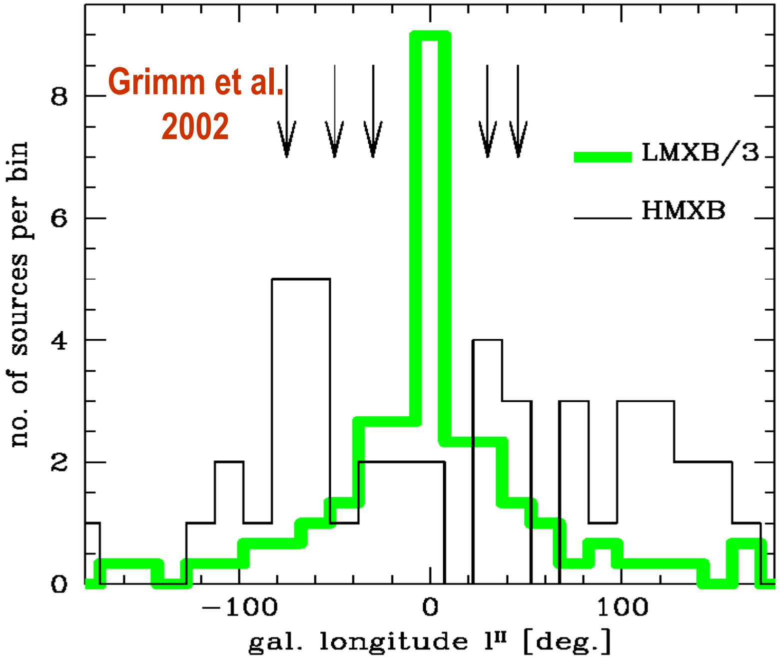
Novae models **(Hernanz et al. 2002)**
^{13}N: abundant BUT too short-lived (e^+ trapped)
^{22}Na: long-lived BUT not enough (factor 40)

POSITRON SOURCES

2. High Energy processes in (or induced by) compact objects

Pair production of positrons, ejected by Outflows/Jets in Low Mass X-ray Binaries (LMXB) ?
(Prantzos 2004)





LMXBs strongly concentrated in low galactic longitude
(Grimm et al. 2002)

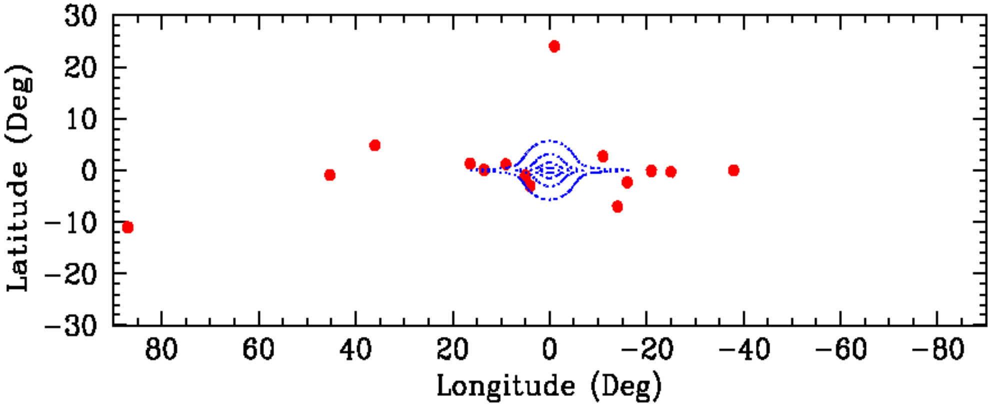
Total X-emissivity of Galactic LMXBs: **$2\ 10^{39}$ erg/s**
($2\ 10^{38}$ erg/s for HMXB, Grimm et al. 2002)

Energy required for 10^{43} e^+/s: **$1.6\ 10^{37}$ erg/s**

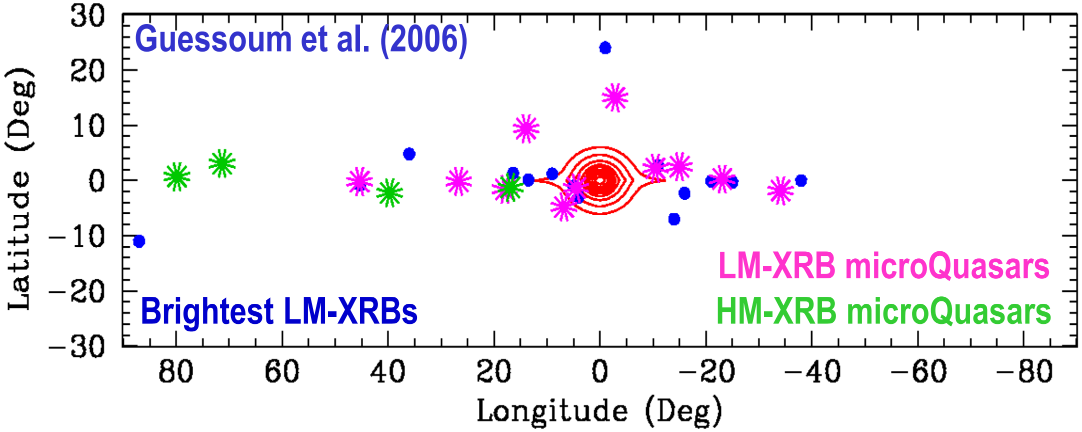
OK, IF about 1% of X-ray radiated energy is used for e^+ formation

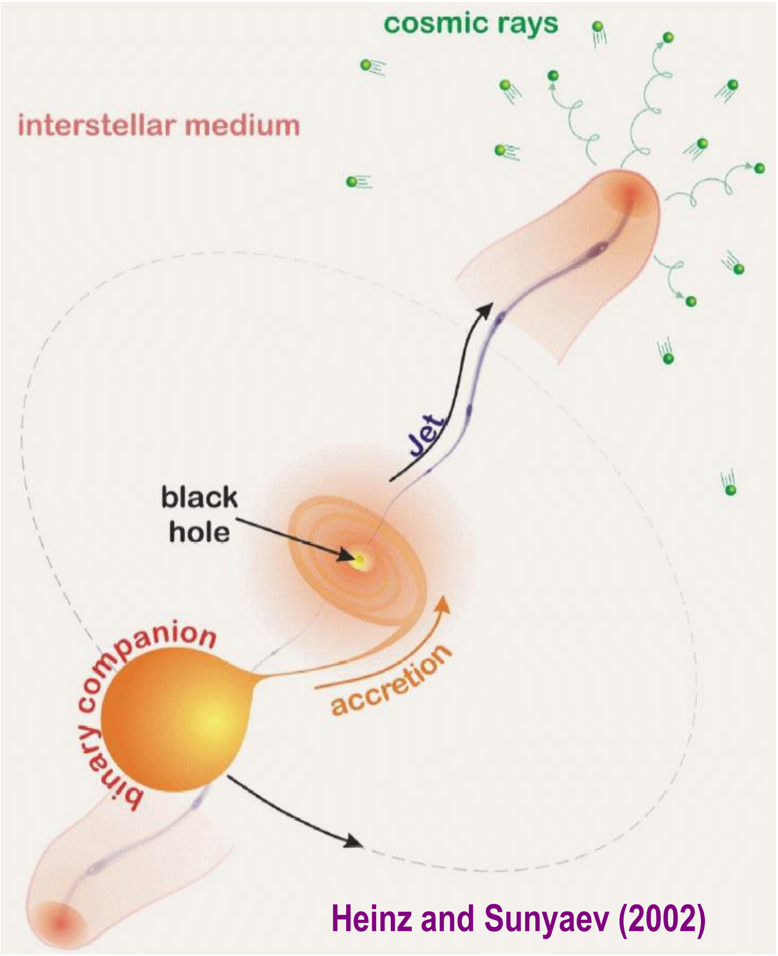
However, 80% of total LMXB X-ray emissivity comes from a dozen or so bright sources, **not clustered in the bulge…**

If $L_{e+} \propto L_X$, morphology is not OK



Jets in Microquasars ?
(sub-class of XRBs, permanent jets in low/hard state)





Galactic population estimated to ~100

Particle content UNKNOWN
(p – e^- or e^- - e^+ ?)

Estimated steady state emissivity of each jet: <10^{41} e^+/s
(= upper limit of SPI measurements)

(but up to 10^{43} e^+/s at eruption)

IF composed of e^- e^+ pairs,
microquasar jets
can provide ~10^{43} e^+/s
Galaxy-wide
(Guessoum, Jean and Prantzos 2006)

Other sources of galactic positrons ?

Annihilation of light dark matter particles ?

(Boehm et al. 2004, Ascasibar et al. 2005)

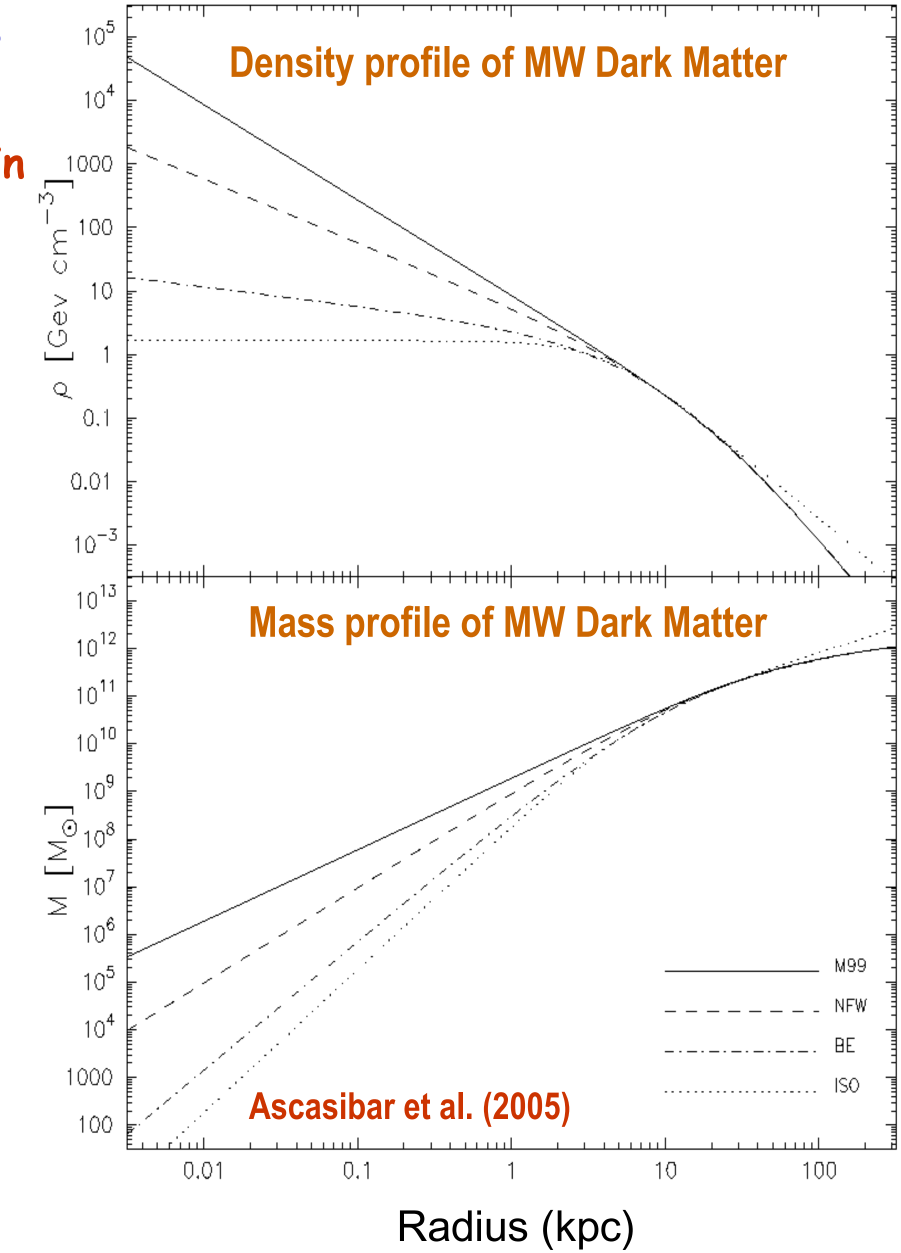
Intensity unknown and **Morphology uncertain**

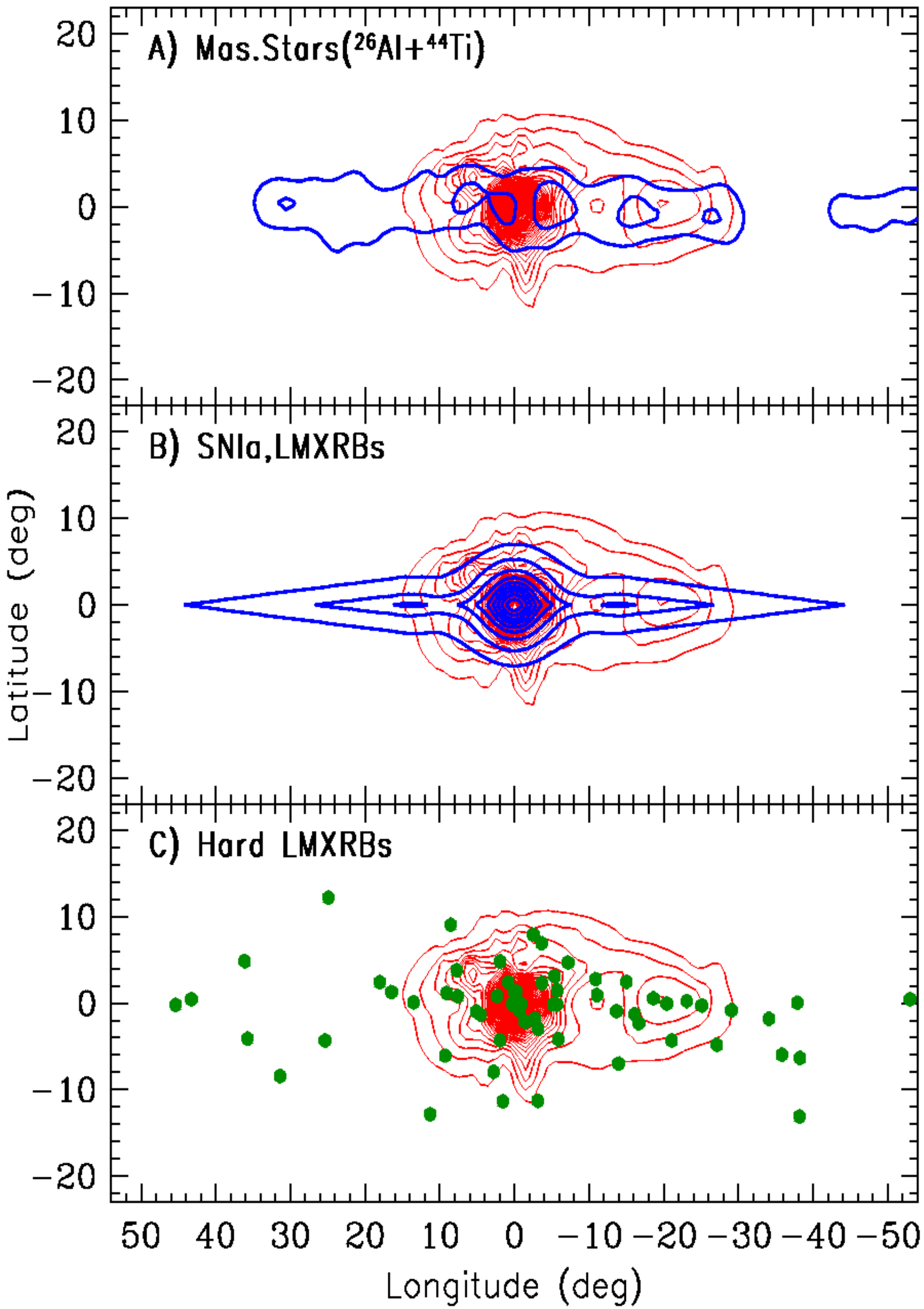
Density profile of DM ρ(DM) unknown
[$\rho(e^+) \propto \rho^2(DM)$]

Mass of DM particles unknown
[In principle: heavy (> GeV), but :
they would produce too many gammas with
E>MeV *Light* scalar particles (<100 MeV)] :
unusual !

Annihilation cross-section unknown
[Depending on assumed mass
and nature of particles,
velocity dependent or independent…]

Recent work (Ascasibar et al. 2005)
suggests that viability of DM model
(a light scalar) also implies:
- new particles (heavy fermion, Z′ boson)
- a value of fine structure constant **α**
different from the recommended one.





In all panels:
Red isocontours: 511 keV observations

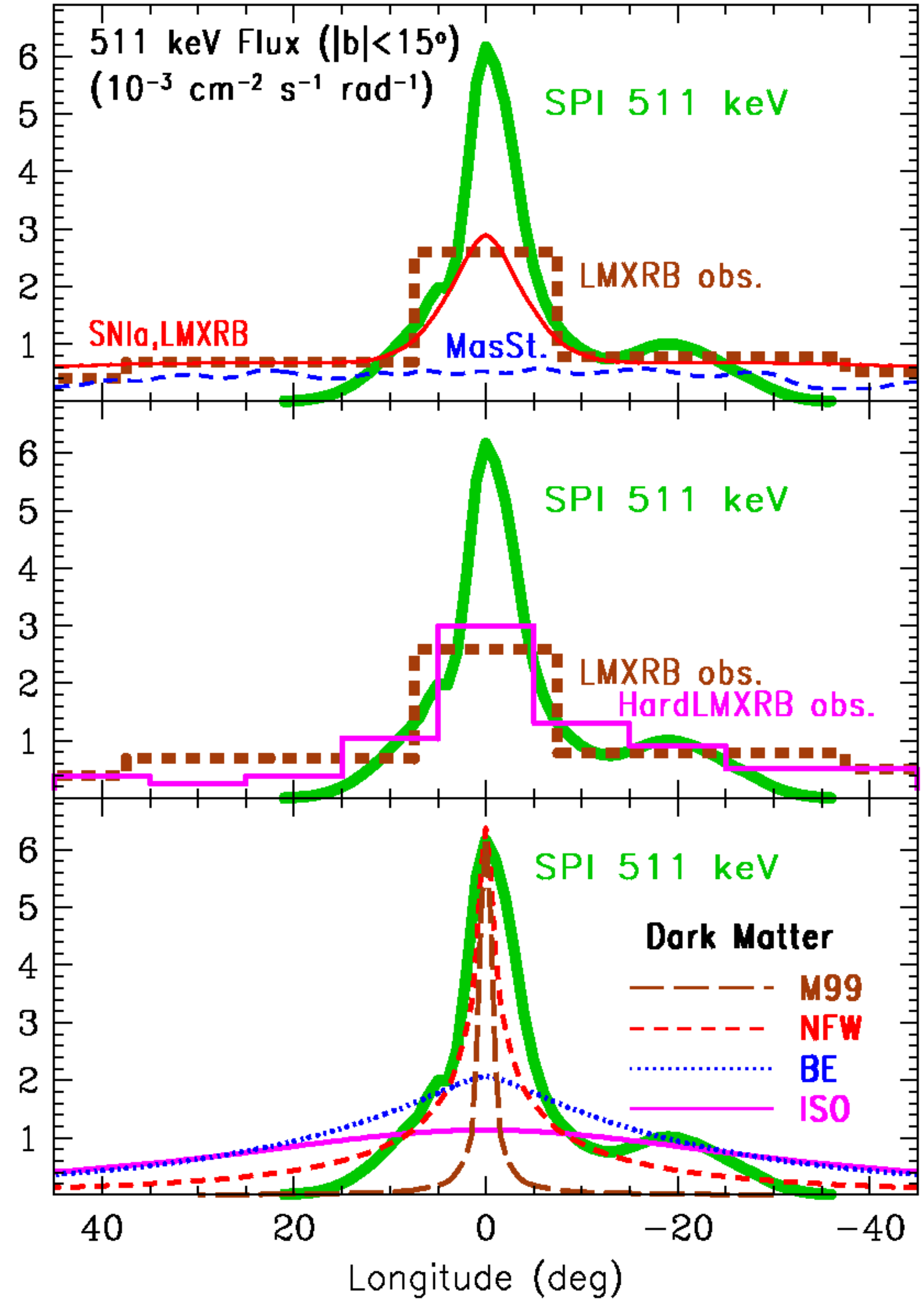
Top panel:
Blue isocontours: 1.8 MeV (Al26) observations
(= Massive stars)

Middle panel:
Blue isocontours: Expected SNIa

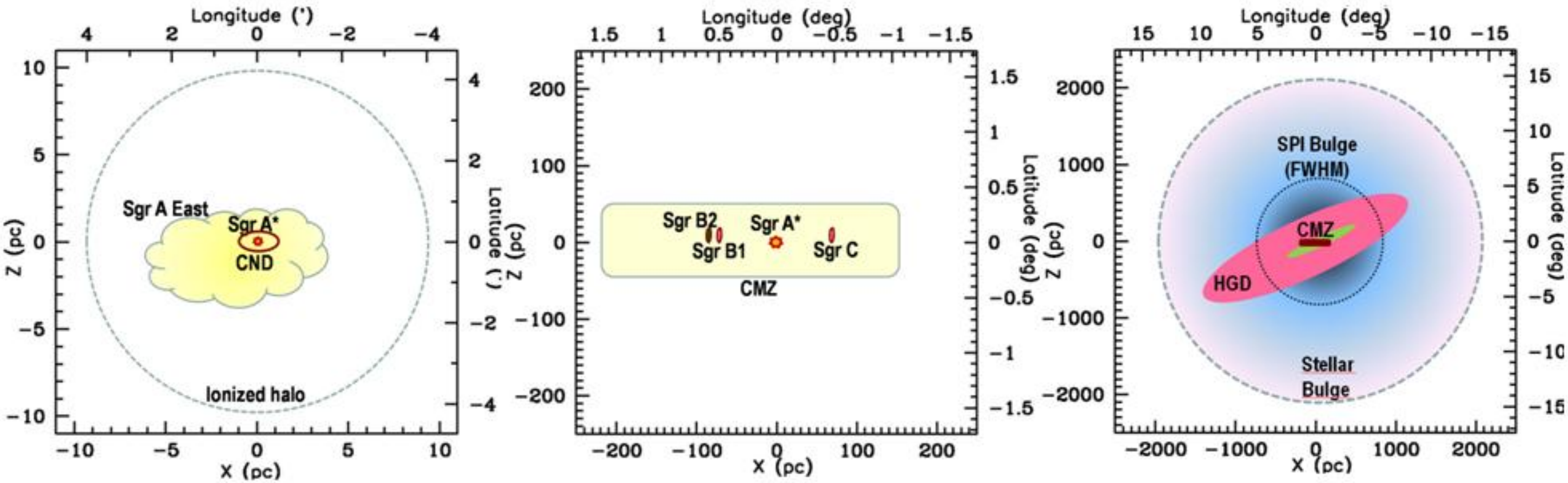
Bottom panel:
Green Dots: Observed Hard LMXRBs
(asymmetric?)

No observed or expected distribution
of known astrophysical sources
is as peaked as
the observed 511 keV one

Only some specific distributions (M99, NFW)
of *annihilating* particles
are as peaked as
the observed 511 keV one
They are apparently ruled out
by observations of dwarf galaxies



The Supermassive Black Hole in the Galactic Center



Positrons must diffuse throughout the bulge, escaping the Central Molecular Zone (CMZ)

Accretion of gas from one (or many) disrupted star(s) up to 10^7 yr ago onto the SMBH and proton acceleration ; secondary e+ produced in p-p collisions (*Cheng et al. 2006*)

Model requires higher activity in the past (10^7 yr AND perhaps 10^3 yr ago in Cheng et al. 2006; or a periodic one in Cheng et al. 2007 and Totani 2007) , since Sgr A* is ~inactive now

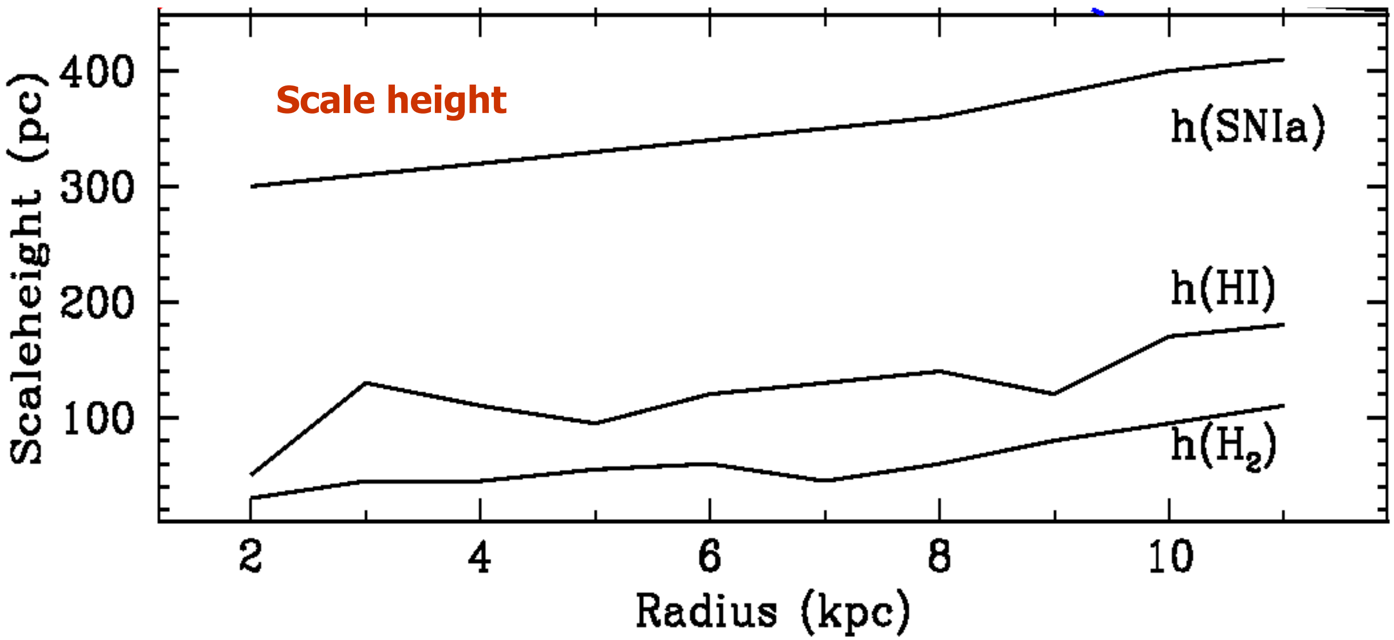
Source	Process	$E(e^+)a$ (MeV)	e^+ rate^b $\dot{N}_{e+}$ (10^{43} s^{-1})	Bulge/Disk B/D	Comments
Massive stars: ^{26}Al	β^+-decay	~1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{24}Ti	β^+-decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	~1	*2*	<0.5	Assuming $f_{e+,esc}$=0.04
~~Novae~~	~~β^+-decay~~	~~~1~~	~~*0.02*~~	<0.5	
~~Hypernovae/GRB: ^{56}Ni~~	~~β^+-decay~~	~~~1~~	~~?~~	~~<0.2~~	Improbable in inner MW
~~Cosmic rays~~	~~p-p~~	~~~30~~	0.1	<0.2	Robust estimate
LMXRBs	$\gamma-\gamma$	~1	*2*	<0.5	Assuming L_{e+} ~0.01 $L_{obs,X}$
Microquasars	$\gamma-\gamma$	~ 1	*1*	<0.5	
~~Pulsars~~	~~$\gamma-\gamma$ / $\gamma-\gamma_B$~~	~~>30~~	*0.5*	<0.2	
~~ms pulsars~~	~~$\gamma-\gamma$ / $\gamma-\gamma_B$~~	~~>30~~	*0.15*	<0.5	
~~Magnetars~~	~~$\gamma-\gamma$ / $\gamma-\gamma_B$~~	~~>30~~	*10 (?)*	<0.2	e^+ yield overestimated (?)
~~Central black hole~~	~~p-p~~	~~High~~	?		
	$\gamma-\gamma$	1	?		Requires e^+ diffusion to ~1 kpc
Dark matter	Annhilation	1 (?)	?		Light scalar required, only NFW profile allowed
	Deexcitation	1	?		Only NFW profile allowed
	Decay	1	?		Ruled out by obs. *and* theor. DM profiles
Observational constraints		<7	2	1.4	

Implicit assumption :

Positrons annihilate close to their sources

Gamma-ray morphology reflects source morphology

Not necessarily true



Most of SNIa positrons released outside the gaseous disk, in low density medium

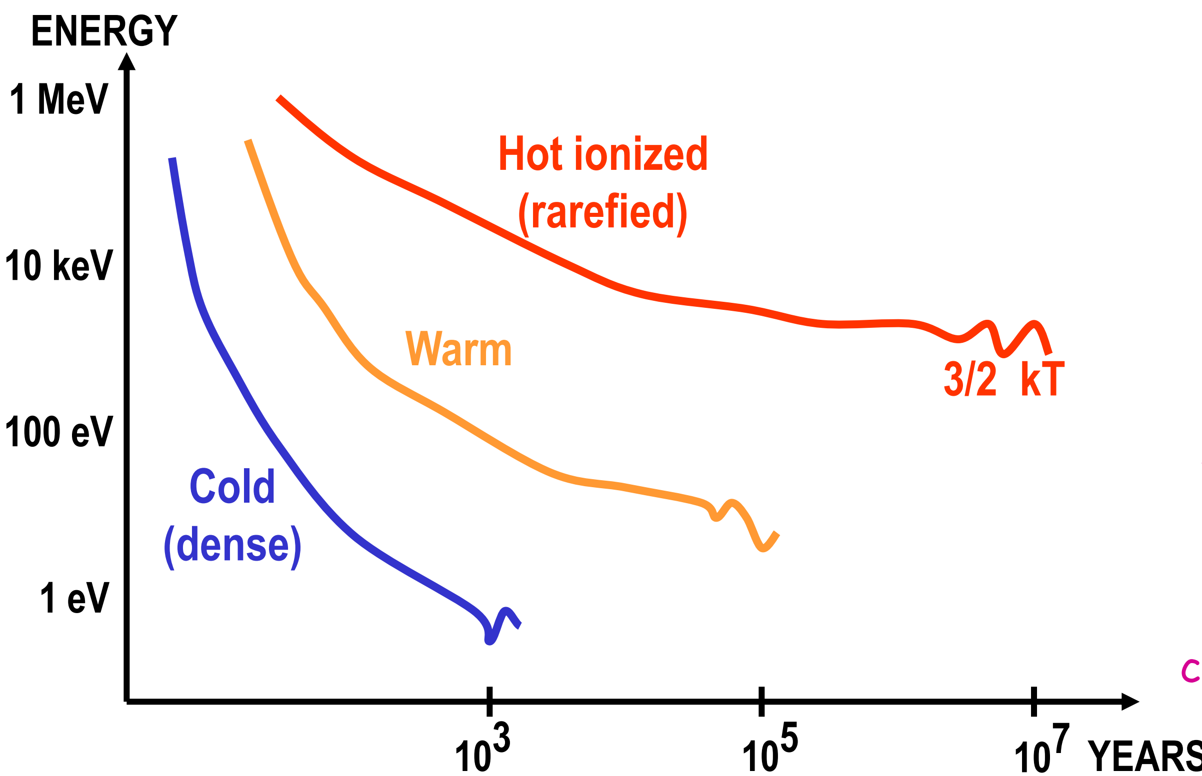
Positron propagation and annihilation in the interstellar medium

Positrons are born hot (> a few hundred keV in any case)

They decelerate (ionization, excitation, Coulomb losses)

They annihilate directly (on bound and free electrons)

Or, **after formation of Positronium**
- (Radiative recombination, in ionized medium)
- (Charge exchange, in neutral medium and E > 6.8 eV)



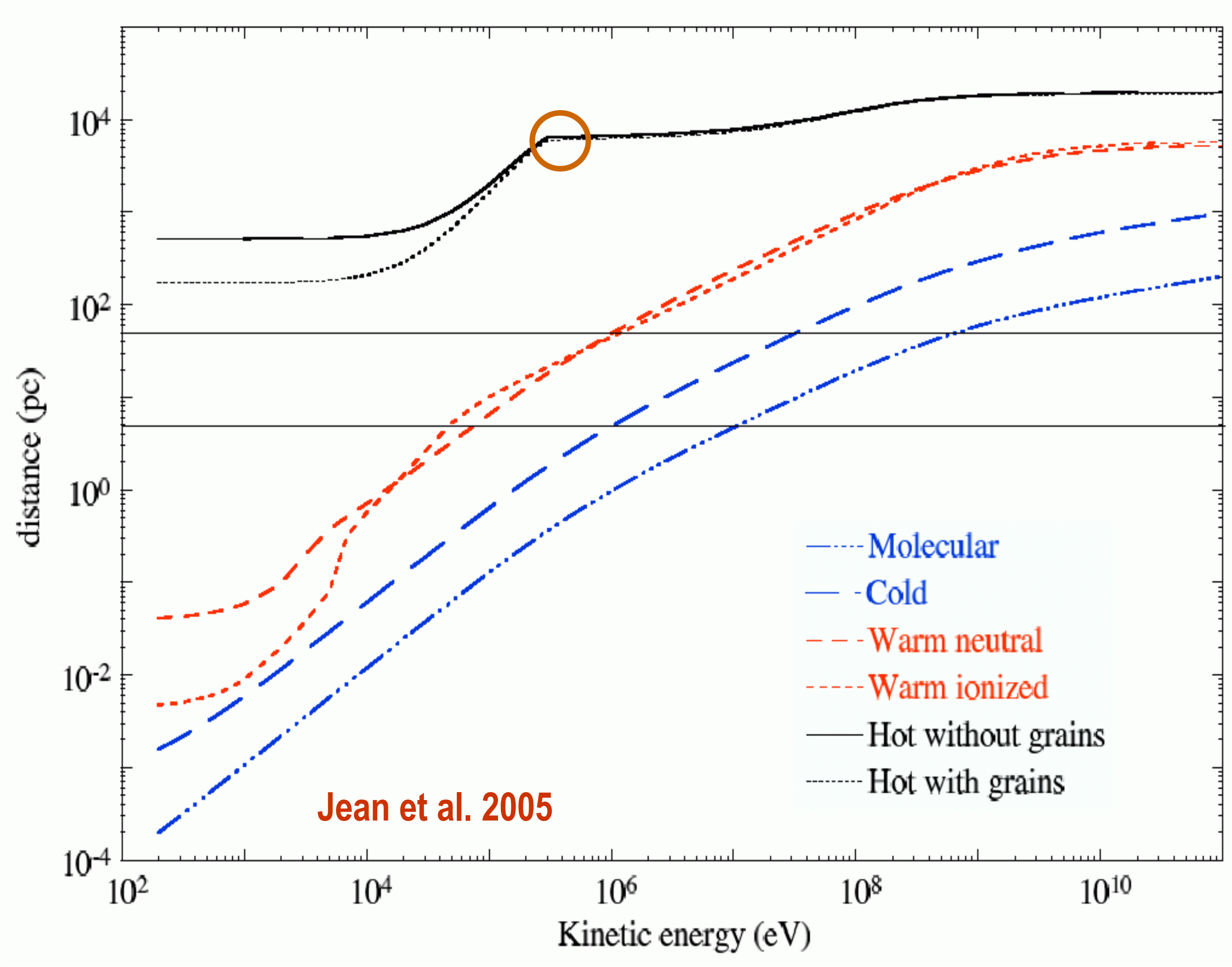
Critical parameters:

Densities and filling factors
of the various phases
of the ISM
(Bussard et al. 1979)

+ the presence of **dust grains**
(Zurek 1983)

+ intensity and
configuration of **magnetic field**

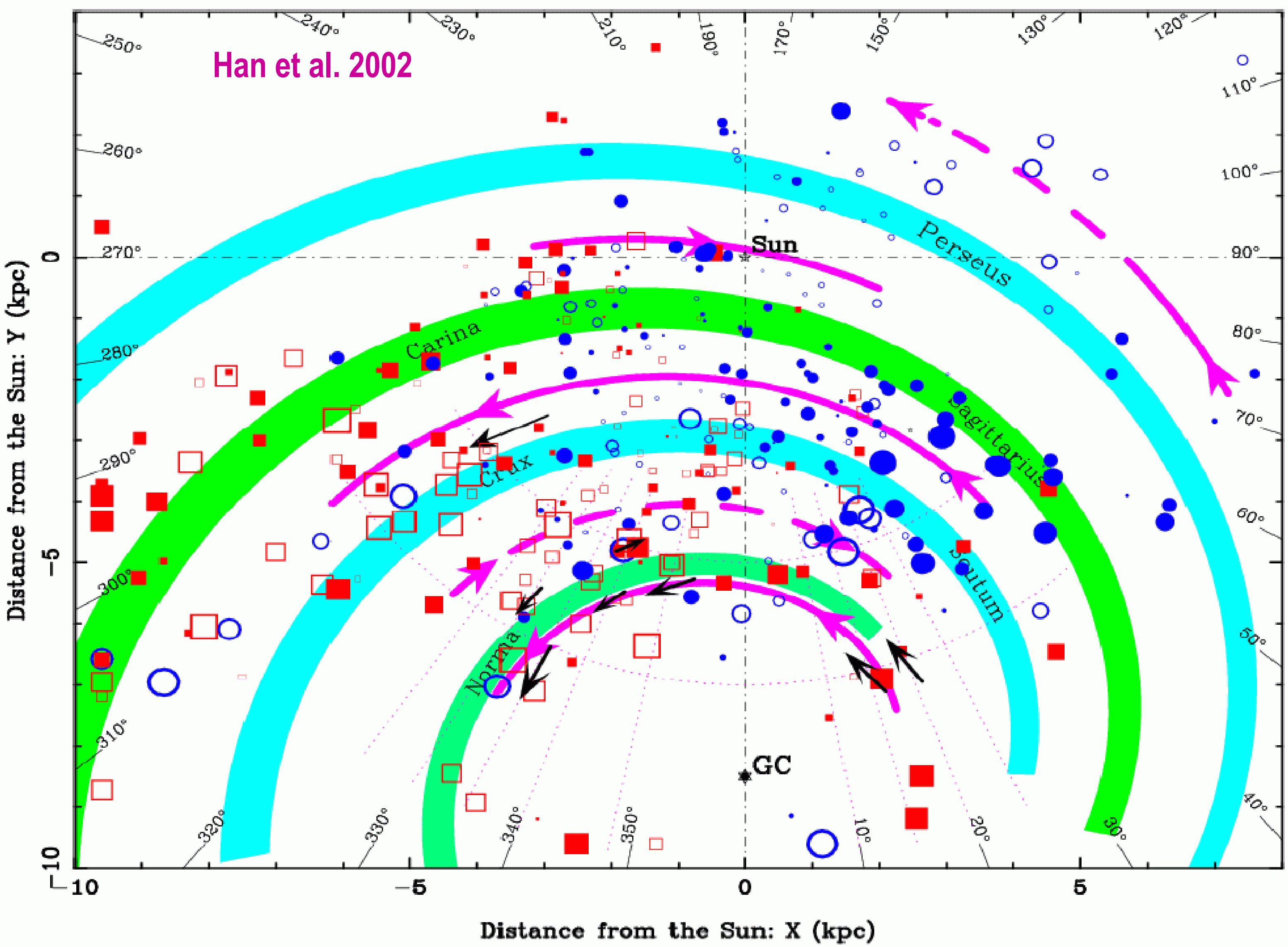
Distance travelled by positrons before annihilating



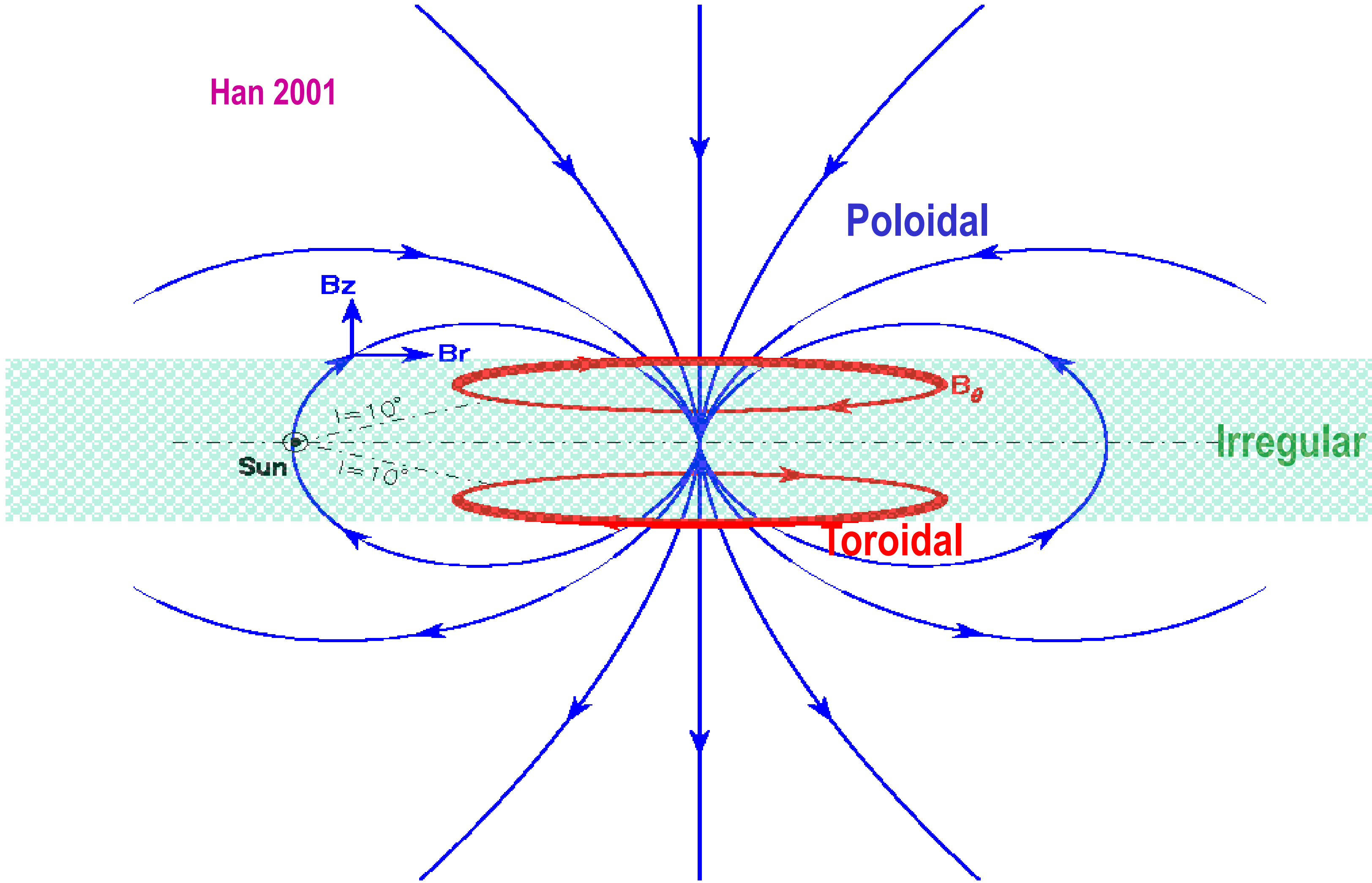
Positrons released in a hot and low density medium
can travel far away from their sources (many kpc)
but **to go where ?**

The Galactic Magnetic field

Irregular field dominant in the disk (a few μG,
but there is also a substantial regular (toroidal) component (1-2 μG),
with intensity inverted between spiral arms

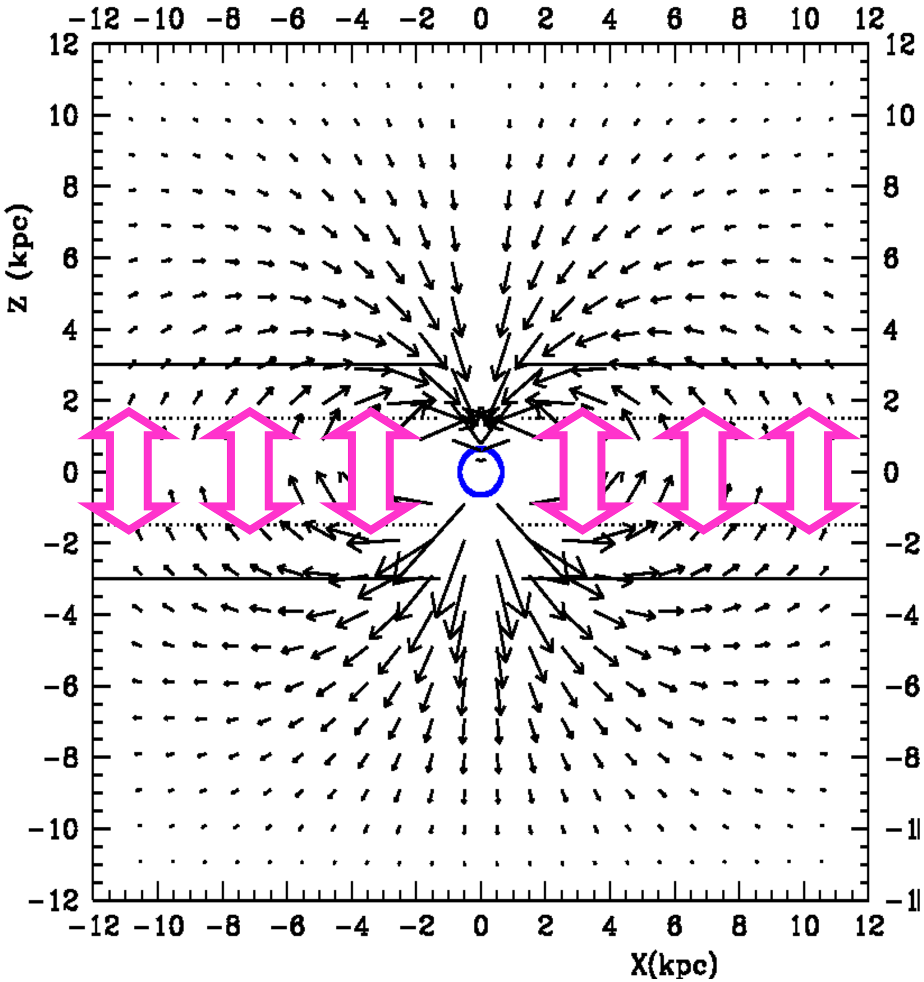


The Galactic Magnetic field



Irregular component (dominant in the disk) ~a few μG at R=8 kpc

Regular component {
- Poloidal $\propto 1/r^3$ and ~0.1 μG at R=8 kpc
- Toroidal $\propto 1/r$ and ~1-2 μG at R=8 kpc



$$B_X = -3\mu_G \, sin\theta \; cos\theta \; cos\phi \; / \; r^3$$

$$B_Y = -3\mu_G \, sin\theta \; cos\theta \; sin\phi \; / \; r^3$$

$$B_Z = \mu_G \, (1 - 3 \, sin^2\theta) \; / r^3$$

Prantzos (2006)
A (difficult to estimate) fraction
of disk positrons
should escape the disk

*(τ_{Annhil} ~ several Myr,
distance ~ several kpc)*

Those positrons could be channeled
by the poloidal magnetic field
- *if* it is a dipole -
towards the bulge, where
they are better confined
(because of the stronger
magnetic field of the bulge)
and they finally annihilate

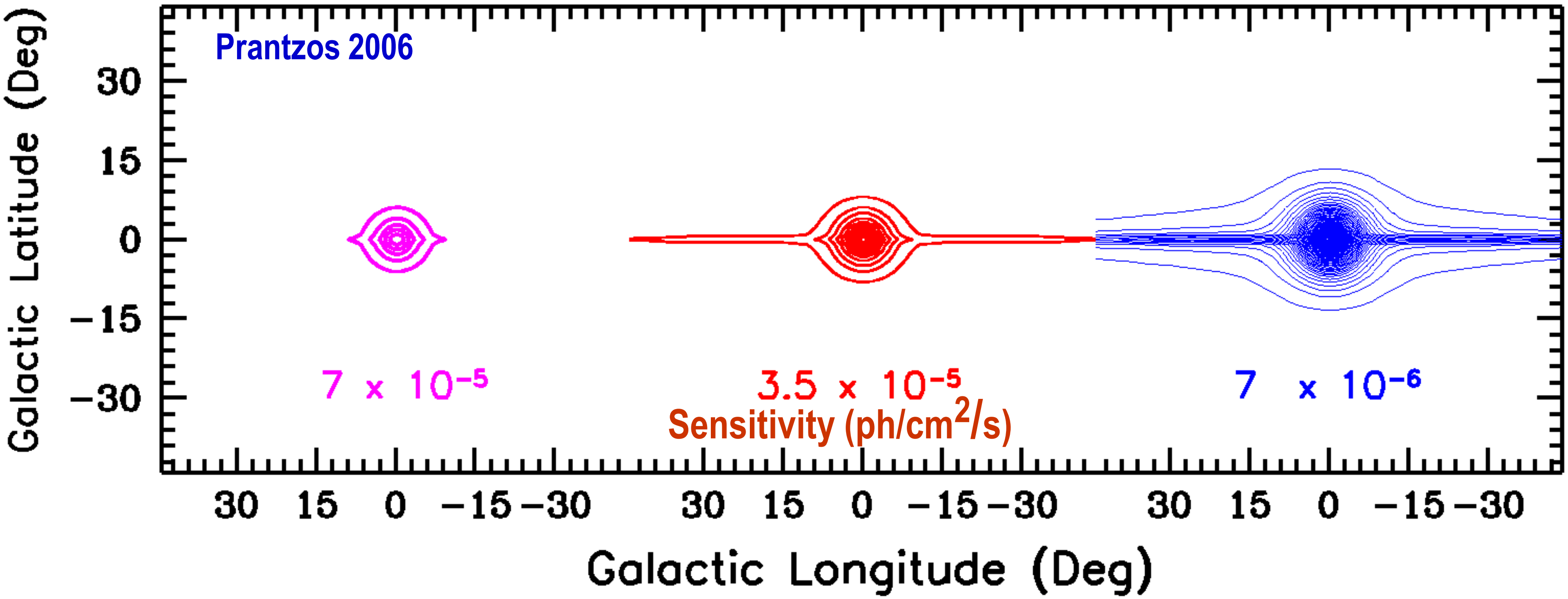
The "magnetic mirror effect"
does not deflect them
back to the disk,
because they enter the poloidal field
with a strong velocity component
parallel to it
(continuity of magnetic field lines from
disk (toroidal) to halo (poloidal) field)

Typical configuration of final positron distribution:

Enhanced Bulge (from transfer of 50% disk SNIa positrons)

+ Thick disk (remaining 50% of disk SNIa positrons away from their sources)

+ Thin disk (positrons from Al26 close to their sources: dense regions in spiral arms)



Summary

The origin of the oldest known and brightest
extra-solar gamma-ray line
remains unknown at present

Its spatial morphology cannot be explained by
conventional astrophysical sources, **unless**
positrons produced in the disk annihilate away from it
or positrons produced in the Galactic center diffuse in the bulge

Possible astrophysical scenarios:

-A specific bulge (=old)? population (LMXRBs, microquasars, ms pulsars?)

- Transfer of disk positrons to the bulge through magnetic field ?
- Diffusion of positrons from central black hole to the bulge ?

Positron propagation is the key issue !

Particle physics solutions ???

(annihilating dark matter particles,
tangle of superconducting cosmic strings…)